NEUROSCIENCE of Consciousness

Neuroscience of Consciousness, 2021, 7(1): niaa027

doi: 10.1093/nc/niaa027
Rapid Communication

What's limbs got to do with it? Real-world movement correlates with feelings of ownership over virtual arms during object interactions in virtual reality

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Abstract

Humans will initially move awkwardly so that the end-state of their movement is comfortable. But, what is comfortable? We might assume it refers to a particular physical body posture, however, humans have been shown to move a computer cursor on a screen with an out-of-sight hand less efficiently (curved) such that the visual representation *appears* more efficient (straight). This suggests that movement plans are made in large part to satisfy the demands of their visual appearance, rather than their physical movement properties. So, what determines if a body movement is comfortable—how it feels or how it looks? We translated an object-interaction task from the real-world into immersive virtual reality (IVR) to dissociate a movement from its visual appearance. Participants completed at least 20 trials in two conditions: Controllers—where participants saw a visual representation of the hand-held controllers and Arms—where they saw a set of virtual limbs. We found participants seeing virtual limbs moved in a less biomechanically efficient manner to make the limbs *look* similar to if they were interacting with a real-world object. These movement changes correlated with an increase in self-reported feelings of ownership over the limbs as compared to the controllers. Overall this suggests we plan our movements to provide optimal visual feedback, even at the cost of being less efficient. Moreover, we speculate that a detailed measurement of how people move in IVR may provide a new tool for assessing their degree of embodiment. There is something about seeing a set of limbs in front of you, doing your actions, that affects your moving, and in essence, your thinking.

Keywords: virtual reality; embodiment; bodily self-consciousness; visuomotor control; sensory prediction; end-state comfort

Introduction

People may adopt an initially awkward posture to increase the 'end-state comfort' of a movement (Rosenbaum *et al.* 1990, 2012). But what is comfortable? We might assume it refers to a physical body posture; however, people have been shown to move less efficiently (curved) such that the visual representation of the movement *appears* more efficient (straight, Flanagan and Rao 1995). Additionally, when people are shown a visual representation of their fast-reaching hand being perturbed along its reach path, they make smooth unconscious corrections to stay on course (Saunders and Knill 2003). This suggests that movement plans are made and updated in part to satisfy the demands of their appearance, rather than their physical movement properties (Wolpert *et al.* 1995). Here, we test whether movement planning priority for particular visual feedback extends to end-state comfort.

When interacting with a real-world object, how you move and how your movements look to you are inseparable. But,

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Received: 30 April 2020; **Revised:** 3 November 2020. **Accepted:** 23 November 2020

using immersive virtual reality (IVR, Slater 2009), we can dissociate these two properties. Here, we test how the visual representation of participants' own limbs during object interactions affects their movements, and if any changes in movements correlated with changes in their subjective experience of the task. Recreating in IVR a task we previously conducted in the real-world measuring eye and body movements of normative and prosthetic-using populations (Boser *et al.* 2018; Lavoie *et al.* 2018; Valevicius *et al.* 2018; Hebert *et al.* 2019; Valevicius *et al.* 2019; Williams *et al.* 2019), participants used an IVR controller to move a virtual pasta box to three shelf locations. Participants completed this task in two body-visualization conditions: (i) Controllers: the positions and orientations of the real controllers were reproduced in IVR; (ii) Arms: virtual hands and arms accurately reflected the positions and orientations of the real controllers.

Despite identical control mechanisms, we noted profound differences in a movement driven entirely by body visualization. When seeing arms, participants extended their real-world wrist in a biomechanically less efficient position such that the virtual thumb and forefinger *appeared* to grasp the side of the pasta box. This does not align with recent evidence from a rapid reach decision-making experiment showing that even in light of changes in task demands, humans tend to minimize biomechanical effort and refrain from altering their movement strategy (Hesse *et al.* 2020). Overall this suggests, like movement-path efficiency (Flanagan and Rao 1995), end-state comfort is largely dictated by the way things look, not how they physically feel. In addition, in this study, participants reported equally high judgments of agency after completing the task in both conditions but reported much higher feelings of ownership when they saw a representation of virtual limbs, supporting claims that agency and ownership are separable components of embodiment (Synofzik *et al.* 2008; Kalckert and Ehrsson 2012). More importantly, we find a significant relationship between changes in movement and feelings of ownership—people who felt more ownership over virtual limbs also showed larger differences in their movements of those limbs. Taken as a whole, these findings suggest that a detailed analysis of movements may be a useful tool in measuring levels of embodiment in IVR.

Materials and methods

Participants

Twenty-one self-reported right-handed undergraduate students provided informed consent to participate in our study. Twenty (one dataset dropped due to software issue) participants (17 male; the average height of 174.45 ± 2.19 cm) were analysed. Ten participants removed their glasses, and one participant was colour blind and was told the colours of the placement targets. Procedures were approved by the University of Alberta Health Research Ethics Board (Pro00085257).

Apparatus and stimuli

Participants donned an HTC Vive head-mounted display (HMD, Vive; HTC and Valve, New Taipei City, Taiwan, and Bellevue, WA, USA, respectively) with a Deluxe Audio Strap. They were immersed in a model of our lab space [built in Unity (Unity Technologies, San Francisco, CA) and using NewtonVR (Today Tomorrow Labs, Seattle, WA, USA)]. The virtual task apparatus consisted of a set of shelves with three placement targets and a pasta box [see Fig. 1a and Supplementary Videos S1 and S2]. Participants held an HTC Vive controller (real controllers) in each hand.

Procedure

Before entering the IVR environment, participants carried out a brief (∼15 s) eye-tracking calibration (PupilLabs GmbH, Berlin, Germany), as eye movements were tracked but are not the focus of the current study. The experiment consisted of two sessions (one per condition) of at least 20 error-free repetitions of an object-interaction task. After each condition, participants removed the HMD and completed a self-reported subjective experience of embodiment survey (based on Longo *et al.* 2008) rating statements on a scale from 1 (Strongly Disagree) to 7 (Strongly Agree).

We replicated a real-world task designed to assess the coordination of gaze and movement during everyday object interactions (Boser *et al.* 2018; Lavoie *et al.* 2018; Valevicius *et al.* 2018; Hebert *et al.* 2019; Valevicius *et al.* 2019; Williams *et al.* 2019). Each trial was initiated with an auditory cue and consisted of three object interactions. First, participants moved the pasta box from the Start/End Target on a table on their right side onto the Mid Shelf Target in front of them. Then, participants moved the pasta box from the Mid Shelf Target to the High Shelf Target by crossing the body's midline. Finally, the pasta box was picked up from the High Shelf Target and placed back on the Start/End Target (Fig. 1a). At the start and end of each trial and after each pasta box placement, participants touched the Home position (pink rectangle in Fig. 1a and b).

We manipulated the visual representation of a participant's end effector. In the Controllers condition (Fig. 1c and Supplementary Video S1), participants saw a virtual model of the real controller. In the Arms condition (Fig. 1d and Supplementary Video S2), participants saw a virtual representation of arms which extended from their torso, with hands that moved naturally with the real controllers [Full Arms VR (Bad Plan Games)]. Condition order was counterbalanced across participants.

The mechanism of control was identical across both conditions—participants used the real controller in their right hand to interact with the pasta box. This interaction was governed by a 5 cm diameter invisible sphere (see Fig. 1b) with its centre located ∼10 cm distal to the participant's real-world hand. The real controller would vibrate when this sphere intersected the pasta box or Home position. Vibration indicated the participant could initiate an interaction with the pasta box by pulling the trigger button. When the trigger was depressed >50%, an interaction began and the pasta box would then move with the real controller until the trigger was released (<50%).

Participants were instructed to move at a comfortable pace and interact with the pasta box on its side. There were coloured targets indicating where the pasta box should be placed for each movement. Additionally, participants were to avoid dropping the pasta box, contacting the apparatus, hesitating or making undesired movements (like scratching one's leg). See Supplementary material for details on the number of recorded and analysed trials.

Data processing

Using custom C# scripts, 3D position and rotation of each real controller, the HMD, pasta box, placement targets and other relevant objects were recorded (90 Hz) on each trial. We used our Gaze and Movement Assessment (GaMA) software (Boser

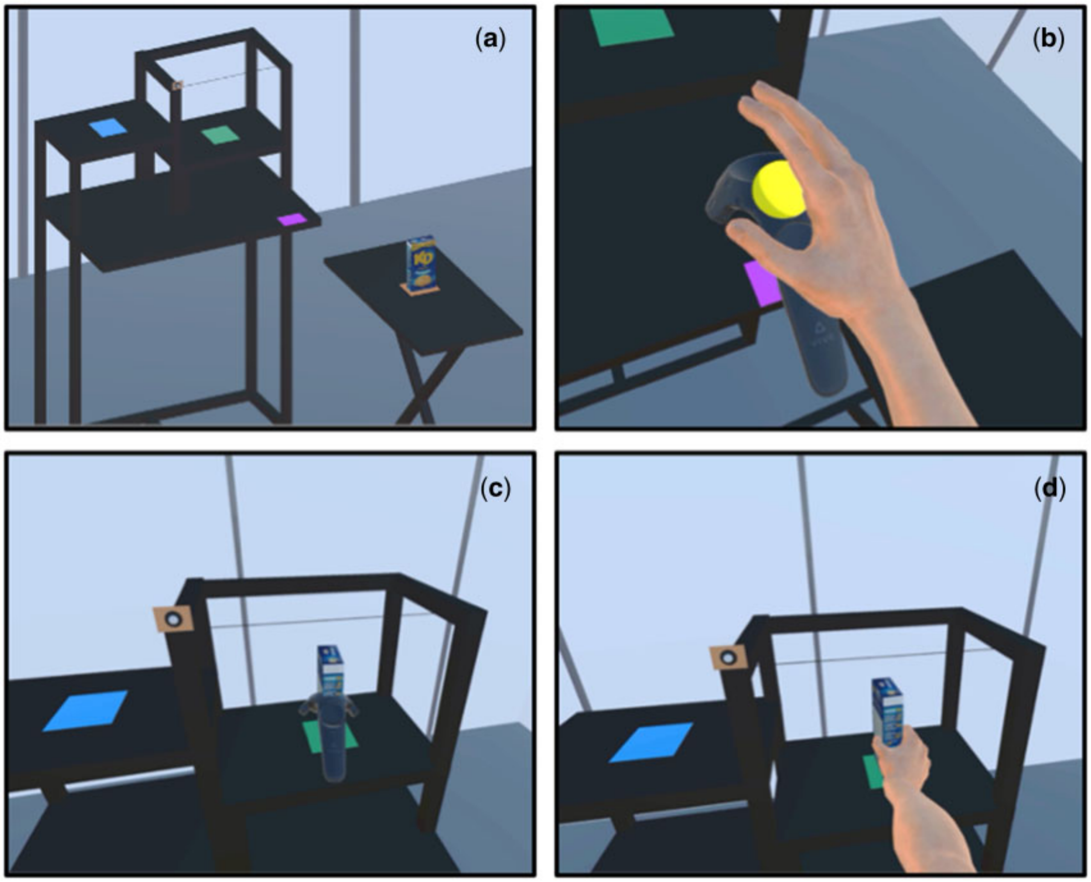

Fig. 1. The task consists of (a) a pasta box beginning on the Start/End Target (orange rectangle) on a side table, the Mid Shelf Target (green rectangle) and High Shelf Target (blue rectangle) where the pasta box is moved to, and the Home position (pink rectangle where participants started, ended and touched in between each movement). In both the Controllers and Arms conditions, participants could interact with the pasta box when (b) an invisible sphere, visualized in yellow, contacted the pasta box which vibrated the real controller signalling an interaction could occur. In the Controllers condition, (c) participants saw a visual representation of the real controller they were holding, while in the Arms condition, (d) participants saw a limb that extended from their virtual torso with a hand that increased grip aperture as it moved towards the pasta box and closed in a clamping fashion upon a trigger-press interaction.

et al. 2018; Hebert *et al.* 2019; Lavoie *et al.* 2018; Valevicius *et al.* 2018; Valevicius *et al.* 2019; Williams *et al.* 2019) to extract the position and orientation of the real controllers and pasta box at the beginning of the three object interactions. This generated a 3D position (In/Out, Left/Right, Up/Down) and orientation (Yaw, Pitch, Roll) for the pasta box (Pasta box Measures—centre of pasta box relative to the centre of placement target) and controller (Hand Measures—centre of interaction sphere relative to the centre of pasta box) for each of the three movements. See Supplementary material for a full description and visual (Supplementary Fig. S1) of these measures.

Statistical analyses

Pasta box and Hand Measures were analysed with a 2 (Condition) × 3 (Target) repeated measures analysis of variance (RMANOVA) using JASP (Love *et al.* 2019). Measures showing exclusively a main effect of Target are discussed in the Supplementary material. Measures with a significant main effect of Condition or a Condition × Target interaction effect are reported if the Greenhouse–Geisser corrected *P*-value was less than 0.05. Any significant interactions were followed by paired *t*-tests comparing Condition at each Target. Full results can be found in Supplementary Table S1.

The self-reported subjective experience of embodiment survey responses (judged on a 7-point scale, see Supplementary material for details) was compiled into components of Embodiment (Ownership, Location, Agency) and Control statements and was analysed with a 2 (Condition) × 4 (Component) RMANOVA, with paired *t*-tests comparing Condition across Component.

Results

Pasta box measures: when seeing arms, the pasta box was placed further from the body and rotated

Participants placing the pasta box on the shelf targets released it further from their body and rotated it more when they saw Arms compared to Controllers.

This was confirmed statistically for the Pasta box In/Out measure with an interaction of Condition × Target, $F(1.523, 28.941) = 4.90$, $P = 0.022$, $\eta^2 = 0.042$, with paired *t*-tests showing a significant difference, $t(19) = 3.20$, $P = 0.005$, Cohen's $d = 0.716$, between Pasta box In/Out at the Mid Shelf Target such that the pasta box placement during Controllers (−1.87 mm, SD = 3.20 mm) was closer to the participant than during Arms (0.27 mm, SD = 3.72 mm). Pasta box Yaw showed a main effect

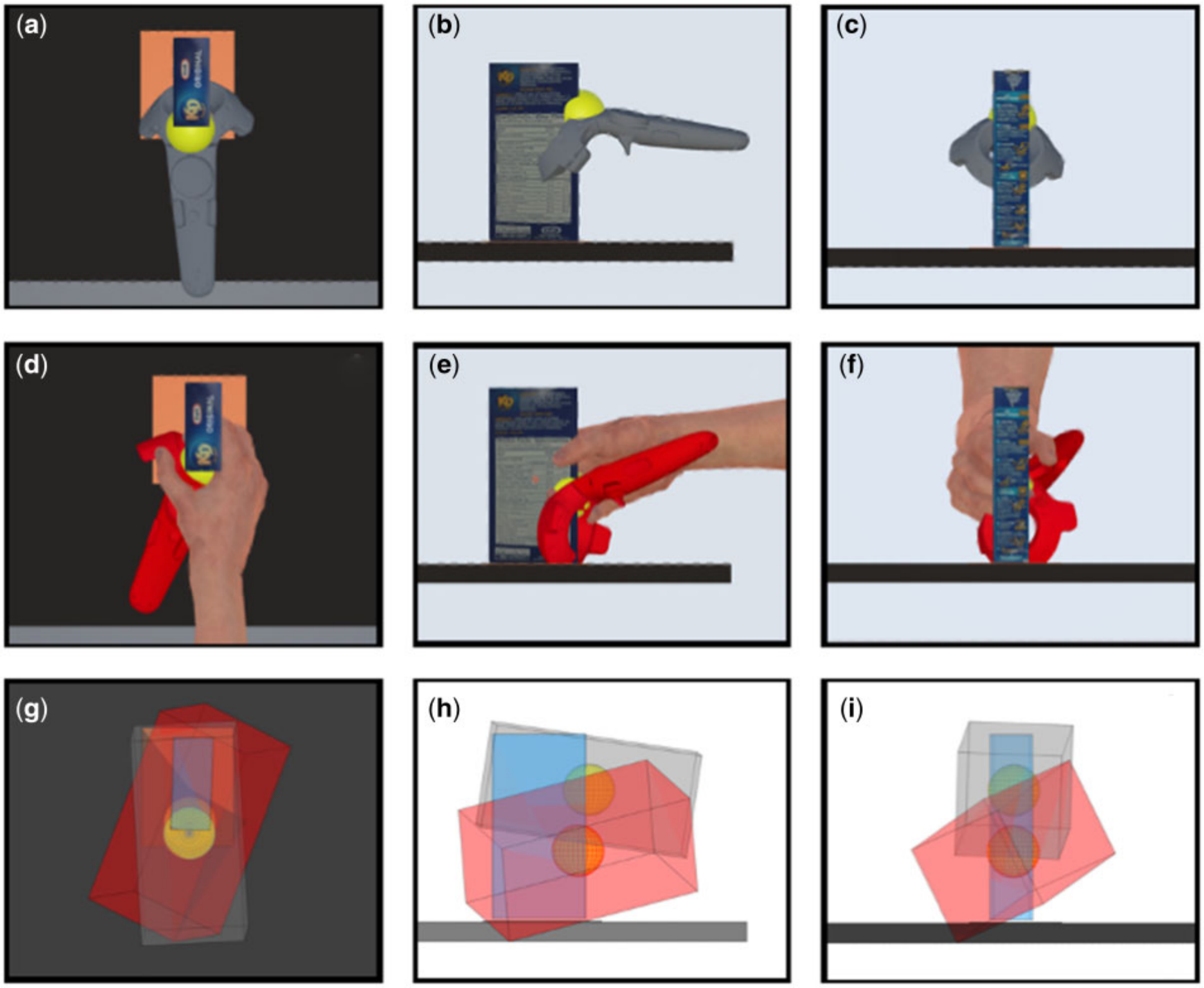

Fig. 2. The average position of the real controller during an interaction at the Start/End Target from all participants during the Controllers condition (in gray), from **(a)** a top-view, **(b)** a side-view, and **(c)** a front-view, and during the Arms condition (in red), from **(d)** a top-view, **(e)** a side-view, **(f)** and a front-view. Software developed to analyse gaze and movement data (GaMA) show the differences in the average position of the real controller rectangle collected from Unity during the Controllers (gray) and Arms (red) conditions from **(g)** a top-view, **(h)** a side-view and **(i)** a front-view. The interaction sphere, which stayed in the same place relative to the real controllers (and was never visible) is shown in yellow in all frames.

of Condition, $F(1, 19) = 9.78$, $P = 0.006$, $\eta^2 = 0.078$, and interaction effect of Condition × Target, $F(1.278, 24.288) = 7.89$, $P = 0.006$, $\eta^2 = 0.034$, with paired t-tests showing significant differences between Arms and Controllers at all three targets: Start/End Target (Controllers = -1.73°, SD = 0.35° and Arms = -1.17°, SD = 0.97°), $t(19) = 2.81$, $P = 0.011$, Cohen's $d = 0.629$ (Fig. 2); Mid Shelf Target (Controllers = -3.23°, SD = 5.45° and Arms = 7.91°, SD = 17.83°), $t(19) = 2.66$, $P = 0.015$, Cohen's $d = 0.598$; High Shelf Target (Controllers = 12.80°, SD = 10.34° and Arms = 25.09°, SD = 23.98°), $t(19) = 3.43$, $P = 0.003$, Cohen's $d = 0.767$. In all cases, the pasta box was more rotated at the start of an interaction when participants viewed Arms (amplified at the shelf locations). The small differences at the first interaction are likely caused by movements occurring before initiation detection.

Hand measures: when seeing arms, the real-world controller was positioned so that the virtual hand formed a grasping pattern

Despite no limitations on how they could move, when seeing Arms participants oriented their real-world wrist in a biomechanically inefficient position to visually orient the virtual limb in a plausible grasping pattern. This meant they held the real controller further into and lower on the pasta box and rotated it so that the virtual hand appeared to have the thumb and forefinger in opposition (see Fig. 2).

The following statistics support this. For position measures, Hand In/Out yielded a main effect of Condition, $F(1, 19) = 53.43$, $P < 0.001$, $\eta^2 = 0.510$, and interaction effect of Condition × Target, $F(1.506, 28.622) = 38.614$, $P < 0.001$, $\eta^2 = 0.080$, with paired t-tests showing significant differences between Arms and Controllers at each target: Start/End Target (Controllers = −48.00 mm, SD = 14.70 mm and Arms = −37.49 mm, SD = 13.67 mm), $t(19) = 4.11$, $P < 0.001$, Cohen's $d = 0.919$ (Fig. 2); Mid Shelf Target (Controllers = −47.83 mm, SD = 15.75 mm and Arms = −26.35 mm, SD = 15.65 mm), $t(19) = 6.39$, $P < 0.001$, Cohen's $d = 1.430$; High Shelf Target (Controllers = −45.11 mm, SD = 15.70 mm and Arms = −14.25 mm, SD = 17.53 mm), $t(19) = 8.84$, $P < 0.001$, Cohen's $d = 1.976$. In the Arms condition, participants extended the real controller further into the pasta box, yielding values closer to the centre of the pasta box. Hand Left/Right yielded a Condition × Target interaction effect,

$F(1.821, 34.604) = 6.59$, $P = 0.005$, $\eta^2 = 0.035$, although no significant pairwise differences were found at any location. Finally, Hand Up/Down yielded a main effect of Condition, $F(1, 19) = 195.31$, $P < 0.001$, $\eta^2 = 0.882$ with participants in the Arms condition (−27.54 mm, SD = 12.46 mm) ending their movements much lower on the pasta box than during the Controllers condition (31.31 mm, SD = 18.45 mm).

For rotation measures, Hand Roll yielded a main effect of Condition, $F(1, 19) = 66.478$, $P < 0.001$, $\eta^2 = 0.722$. Participants seeing Controllers kept the real controller nearly level (0.45°, SD = 2.38°), while during Arms, it was significantly rotated (−25.16°, SD = 15.05°). Hand Yaw yielded a main effect of Condition, $F(1, 19) = 130.496$, $P < 0.001$, $\eta^2 = 0.774$, and interaction effect of Condition × Target, $F(1.196, 22.721) = 4.812$, $P = 0.033$, $\eta^2 = 0.005$, with subsequent analysis showing significant differences between Arms and Controllers at each target: Start/End Target (Controllers = 4.66°, SD = 7.35° and Arms = −24.82° SD = 13.58°), $t(19) = 10.93$, $P < 0.001$, Cohen's $d = 2.444$; Mid Shelf Target (Controllers = −0.74°, SD = 7.72° and Arms = −35.16°, SD = 16.27°), $t(19) = 10.55$, $P < 0.001$, Cohen's $d = 2.360$; High Shelf Target (Controllers = 1.58°, SD = 8.11° and Arms = −34.16°, SD = 19.15°), $t(19) = 10.33$, $P < 0.001$, Cohen's $d = 2.309$. When seeing Arms, participants rotated their real hand such that the virtual hand positioned the finger and thumb opposed (amplified at the shelf locations). By comparison, during Controllers, participants moved straight into the pasta box and did not rotate their hand. Finally, Hand Pitch yielded a main effect of Condition, $F(1, 19) = 39.947$, $P < 0.001$, $\eta^2 = 0.515$. During Controllers, participants angled the real controller upwards (18.66°, SD = 16.43°), while during Arms, participants angled it downwards (−4.89°, SD = 5.88°).

Embodiment: when seeing arms, participants reported greater feelings of ownership

Full details of the self-reported subjective experience of embodiment survey and the response results are presented in Supplementary Table S2. We compiled participant responses to the statements into the three components of Embodiment (Ownership, Location, and Agency) from Longo *et al.* (2008), and also a Control statement component. Here, control statements were those that were not expected to differ between the Arms and Controllers conditions but were meaningfully related to the task (e.g. ease of using the trigger on the hand-held controller, difficulty of the task, real and virtual world synchronization). The RMANOVA yielded a main effect of Condition, $F(1, 19) = 4.679$, $P = 0.043$, $\eta^2 = 0.072$, and Component, $F(2.258, 42.910) = 5.842$, $P = 0.004$, $\eta^2 = 0.113$, and an interaction effect of Condition × Component, $F(2.378, 45.183) = 5.637$, $P = 0.004$, $\eta^2 = 0.036$. To examine the interaction, we ran four follow-up paired t-tests comparing Arms and Controllers at each of the four Components and adjusted the alpha to accept t-tests with P-values less than 0.0125. Here, the Ownership component was found to be significantly higher in the Arms condition [Arms = 5.20, SD = 1.23 and Controllers = 3.98, SD = 1.74, $t(19) = 3.05$, $P = 0.007$, Cohen's $d = 0.682$], while all other components did not differ (Fig. 3a).

Changes in feelings of ownership correlates with changes in movement

Next, we aimed to see if changes in self-reported feelings of ownership correlated with changes in the movement measures. Specifically, we correlated (i) The average 3D distance in real controller placement on the pasta box between the two conditions at each interaction with (ii) the difference in Ownership rating between the two conditions. We found a strong correlation between the difference in real controller placement and Ownership rating between the two conditions ($r = 0.519$, $P = 0.019$), compared to weak and insignificant findings for Location ($r = 0.295$, $P = 0.207$), Agency ($r = 0.369$, $P = 0.110$) and Control ($r = 0.298$, $P = 0.201$). As well, we tested the strength of the evidence in support of the hypothesis that a positive correlation exists between the difference in 3D controller placement and Ownership using Bayes factors (BF). This analysis revealed that the hypothesis that there is a positive correlation predicts the data just over seven times better than a null hypothesis of no correlation ($BF_{+0} = 7.118$) at a moderately robust level. In other words, strong evidence supports the relationship wherein the further apart a participant positioned the real controller when grasping the pasta box during the Arms versus Controllers condition, the higher their self-reported feelings of Ownership for the virtual Arms was (Fig. 3b).

Discussion

This experiment used IVR to test whether participants would alter their real movements to create more 'comfortable' visual feedback. Indeed, when seeing virtual arms as compared to virtual controllers interacting with a virtual pasta box, participants moved their real hand such that the virtual limb was lower, extended further from their body, and rotated in three dimensions to make the virtual thumb and forefinger appear opposed, as a real-world limb would if it were interacting with this object (Lukos *et al.* 2007).

Stark movement differences were accompanied by survey responses indicating that virtual arms induced a greater sense of ownership than virtual controllers, while reported sense of agency was high in both conditions. This increase in ownership for a realistic arm-like object has been well documented in other domains (e.g. Botvinick and Cohen 1998) including in IVR (Slater *et al.* 2008; Argelaguet *et al.* 2016; Lin and Jörg 2016; Pyasik *et al.* 2020) and can be enhanced via visual feedback that synchronizes with a person's physical respiration (Monti *et al.* 2019) or heart rate (Suzuki *et al.* 2013). As well, visual discontinuity of a virtual limb being passively observed by a participant has been shown to decrease the feeling of ownership and sense of agency of that limb (Tieri *et al.* 2015), which is likely a contributor to our findings of decreased ownership over the virtual controllers compared to the virtual arms. As mentioned earlier, it has been shown that agency and ownership are dissociable aspects of the feeling of embodiment in the real world (Longo *et al.* 2008; Synofzik *et al.* 2008; Kalckert and Ehrsson 2012) and in IVR (Lin and Jörg 2016). Our results support this, as participants' reported sense of agency was high in both conditions, while sense of ownership was much greater for the virtual arms than the virtual controllers. Although it has been widely shown that ownership over a body will impact the sense of agency of that body, our results support the notion that there are other factors at play in creating a sense of agency (Pyasik *et al.* 2019). In our study, virtual controllers may be more like using a tool like a hammer in the real world. We understand that we have agency over the hammer, but that it is not part of our body. When seeing a pair of virtual arms moving like real limbs, these arms may go one step further and begin to replace our own limbs in our body schema, creating increased ownership. It has been shown previously that ownership over a limb influences sensorimotor behaviour (Burin *et al.* 2019). Our findings support this

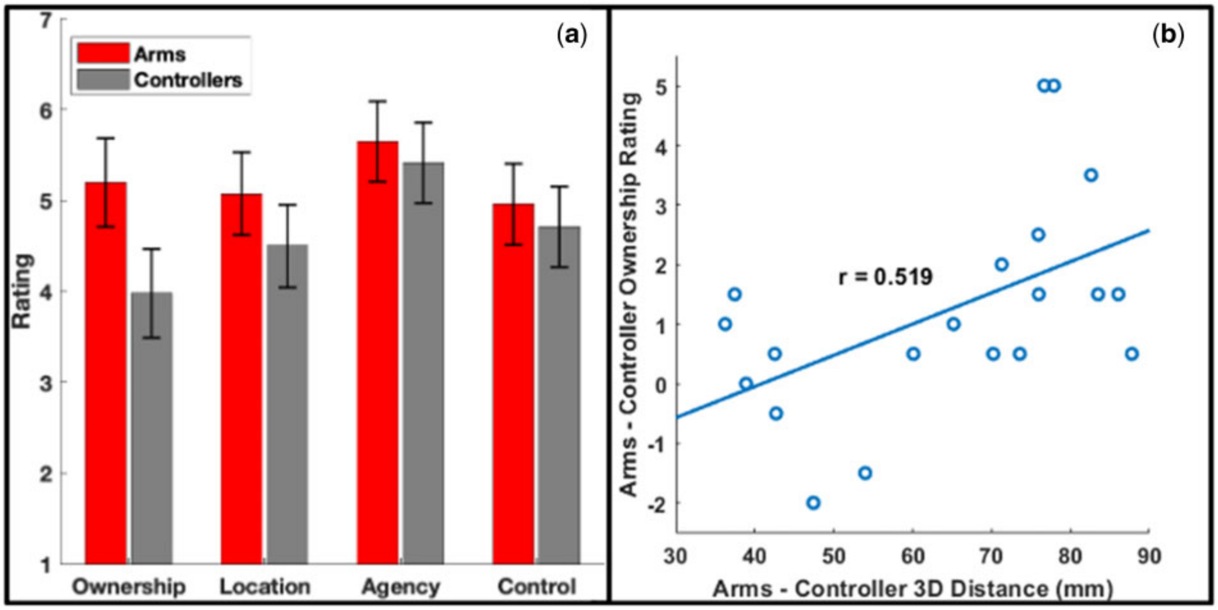

Fig. 3. (a) The average ratings to the statements of the self-reported subjective experience of embodiment survey compiled into the components of Embodiment (Ownership, Location, and Agency) and a Control statement component across both conditions. The error bars are the 95% CI of the difference between conditions for that component. (b) The correlation between the difference in real controller 3D position and Ownership rating between the Arms and Controllers conditions.

and show that humans will move their own real-world limb into biomechanically inefficient positions to elicit a plausible grasping position in a virtual limb that they experience ownership over.

Importantly, we found a relationship between these two measurement types (physical movement and subjective report) which rarely get reported together. That is, not only did a change in visual feedback of a person's body change how they moved *and* how they felt about ownership over those bodies, but these two properties were significantly correlated (see Fig. 3b). Participants who felt more ownership over the Arms versus Controllers tended to be the same participants who were more willing to change their physical movements to accommodate the difference in visual feedback. Previous work has shown that during the rubber-hand illusion, participants will not only feel as though their real hand is drifting towards the rubber hand but that when possible through use of a horizontally sliding board, participants' real hands will actually drift towards the rubber hand (Asai 2015). Not only that but when participants' hands are not able to slide, they generate force that would move their real hand in line with the rubber hand (Asai 2015). In a domain where features of subjective experience are notoriously difficult to quantify, we submit that capturing measures of physical movement behaviour can serve as an important objective correlate to changes in the experience of embodiment. The beauty of IVR platforms is that this movement data is a necessary component of the IVR experience and is natively available. We must note that a major limitation of this study is that an appropriate control condition is missing. To more fully compare the effects of visual representation of virtual arms, a comparison to non-arm-like objects with similar dimensions extending from the torso should be tested (Pyasik *et al.* 2020).

More broadly, these findings contribute to models in which body memory influences behaviour (Riva 2018), bodily self-consciousness relies on the integration of multiple sensory modes (Blanke 2012), and motor commands are generated together with predictions of their sensory outcomes (Adams *et al.* 2013). In brief, these models rely on the integration of bottom-up sensory components, with continuous tuning by top-down cognitive predictions. As a person is acting, top-down motor outputs are created, as are predictions of what the incoming bottom-up sensory information should be for that action. Real bottom-up sensory information is acquired, and modulation of the top-down motor outputs occurs based on the error between the real sensory information and the sensory prediction. The impact that action intentions have been found to have on perceptions of incoming sensory information is well documented, with the perceived results of an action pulled closer in time to the action itself as participants perceive they are the cause of the result (Haggard *et al.* 2002). Reinforcing or violating certain sensory predictions can induce various misperceptions, in IVR (see Gonzalez-Franco and Lanier 2017 for review) and the real world (e.g. Haggard *et al.* 2002). Presenting participants with the visual representation of virtual arms created a set of motor-induced sensory predictions (e.g. that thumbs should oppose forefingers) which they sought to confirm by altering their movements. Although, a recent study questions the validity of the results of rubber-hand illusion experiments, finding significant correlations between embodiment measures and hypnotizability (Lush *et al.* 2020). Further studies involving the manipulation of an embodiment should account for participant perceptual suggestibility.

The results of our study also align with models of how the sense of agency develops (Synofzik *et al.* 2008). Here, prediction error of external percepts may be enough for ownership to develop but is not enough for the sense of agency to occur, which requires that motor intentions and resulting motor-related sensory feedback are integrated into a unified bodily awareness (Tsakiris *et al.* 2006). In our study, participants would have the motor intention of moving either the virtual controller or virtual arm to interact with the pasta box. When they successfully manipulated the box, they would receive visual sensory feedback of this, and would thus develop agency over their actions in both conditions. Our results are consistent with this hypothesis since the judgement of agency is similar for both the limb (Arms) and non-limb-like (Controllers) effectors. These results highlight the distinctions between agency and ownership, with the sense of agency perhaps relying more on motor intentions and sensory outcomes, while the sense of ownership being largely influenced by the visual appearance of the effector (e.g. Pyasik *et al.* 2020).

Conclusions

Previous work shows that participants will adopt an initially awkward posture to increase the end-state comfort of the movement (Rosenbaum *et al.* 1990, 2012), implying that physical body posture dictates movement planning. But, other work demonstrates that participants controlling a cursor with an out-of-sight hand move in a way so that the cursor looks like it moves straight, even though their hand moves in a curved path (Flanagan and Rao 1995). This aligns with movement planning theories suggesting that predicted visual feedback may be the primary driver of motor control, rather than posture (Wolpert *et al.* 1995). Here, using the power and flexibility of IVR, we precisely measured real-world movements to test whether participants would change their behaviour to create more 'comfortable' visual feedback when seeing a virtual hand versus a virtual controller. Profoundly, in no way required by the task and inconsistent with recent research putting an emphasis on biomechanical efficiency (Hesse *et al.* 2020), participants adopted biomechanically inefficient physical postures such that the virtual limb *appeared* like a real-world limb would if it were interacting with an object (Lukos *et al.* 2007). These altered movements correlated with stronger participant-reported feelings of ownership towards the set of virtual arms compared to virtual controllers along with comparably high agency ratings in both, offering a tantalizing clue that embodiment is more tightly bound to the visual representation of our body than our actual body posture. Further, this study offers strong support that visual feedback plays a dominant role in movement planning (Flanagan and Rao 1995; Wolpert *et al.* 1995), contributing to motor control theories that down-weight considerations of posture and proprioceptive information and place a premium on generating visual feedback that matches visual sensory predictions of movements. Finally, most excitingly, our results suggest we may be able to harness the readily available movement data from IVR experiences as a means of providing objective quantification of questionnaire-reported changes in subjective experience.

Supplementary data

Supplementary data is available at *NCONSC Journal* online.

Acknowledgements

E.L. is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) with a Postgraduate Doctoral Scholarship (PGSD3-519162-2018). C.C. receives funding through an NSERC Discovery Grant (RGPIN-2014-05248), the Canadian Foundation for Innovation John R. Evans Leaders Fund, and a Canadian Institute for Advanced Research Catalyst Grant. Both authors thank these organizations for their ongoing support, as this research would not be possible without it.

Data availability

Data not publicly available but will be provided upon email request to the authors.

Conflict of interest statement. None declared.

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